The single-photon response of photomultiplier tubes to xenon luminescence

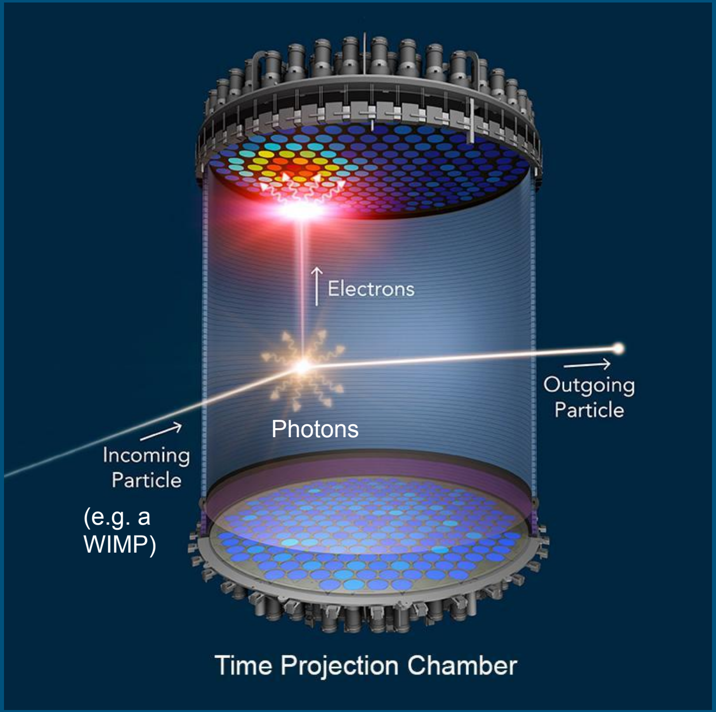
Brais López Paredes (Imperial College London)

with special thanks to Theresa Fruth (University of Oxford), Henrique Araújo (Imperial) and the LZ collaboration

LIDINE 2019, Manchester

Direct dark matter detection in LXe TPCs

- Searching for very low-E nuclear recoils (NR)
- Prompt scintillation (S1) plus free electrons
- Electric field extracts electrons into gas
- Electroluminescence light (S2)
- 3D reconstruction with S2 (XY) and S1-S2 delay (Z): fiducialisation
- Background discrimination: S2/S1 ratio different for ER (bkg) and NR (signal)
- Photomultipliers for 175 nm photon detection
- Require coincident photons to avoid spurious S1s from dark counts (DCs)



Brais López Paredes, Imperial College London

Photomultiplier tubes

The current choice for LXe TPCs:

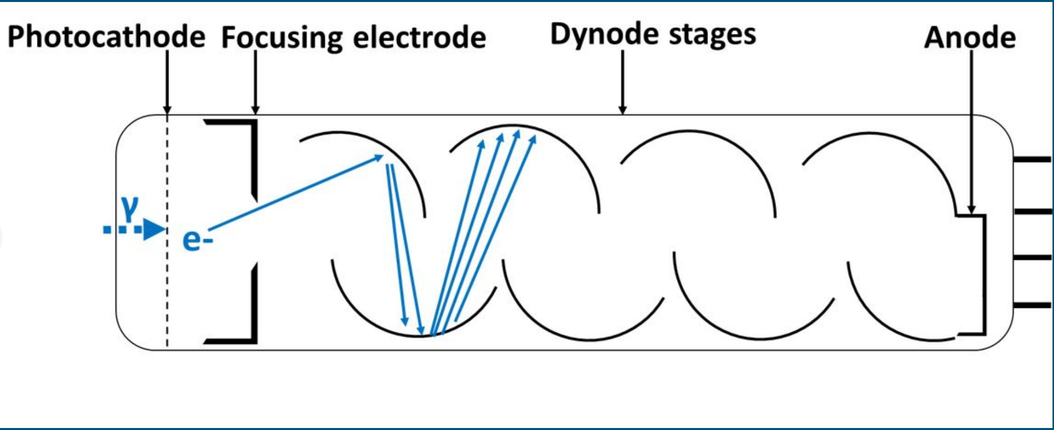
- Hamamatsu R11410
- 3-inch quartz window
- Quantum Efficiency:
  - ~30% at 175nm
- Low dark count rate
  - ~O(10)Hz at LXe temperatures
- Low radioactivity:
  - ~mBq/PMT in U/Th (late)

Values in (mBq/kg)									
Material	Mass screened (g)	Mass /PMT (g)	$^{238}U_e$	$^{238}U_l$	$^{232}Th_e$	$^{232}Th_l$	^{60}Co	^{40}K	^{210}Pb
Metal Bulb[2]	506	78	*17.9*	*0.90*	*1.67*	*1.28*	-	*6.41*	-
Dynode[1]	530	7.2	*216*	*2.02*	*4.10*	*3.40*	4.00	*4.60*	-
Shield Plate[1]	519	4	*77.0*	*3.10*	*5.00*	*3.20*	4.60	*6.00*	-
Faceplate[2]	1168	30	*11.0*	*0.67*	*1.00*	*0.80*	-	*4.00*	-
Insulator plate[2]	838	8.6	*20.9*	*1.05*	*1.63*	*1.16*	-	*6.28*	-
Electrode Disk[1]	517	9.9	*203*	9.50	*4.30*	14.0	8.50	*9.60*	-
Faceplate Flange[1]	532	18	*162*	*2.75*	*3.80*	*4.20*	12.5	*14.4*	-
Ceramic Stem[1,3]	757.5	15.7	105	20.0	12.9	9.60	-	110	5.60
Ceramic Stem Flange[1]	1568	14	*198*	*0.63*	*2.32*	*0.84*	12.0	*3.30*	-
Aluminium Ring[1]	506	0.6	*62.0*	*1.23*	2.33	*0.94*	*0.34*	*8.50*	-
Getter[1]	7	0.07	*2508*	*39.0*	*133*	*102*	*9.40*	*173*	-
Stem Coating	100	0.00012	*22.0*	178	*9.00*	7.50	-	61.0	539
Mass Weighted Ave		**186.1**	***71.6***	***3.20***	***3.12***	***2.99***	***2.82***	***15.4***	***0.47***
Total (mBq/PMT)		**186.1**	***13.3***	***0.60***	***0.58***	***0.56***	***0.53***	***2.87***	***0.09***

LZ Technical Design Report - arXiv:1703.09144

VUV photon detection process

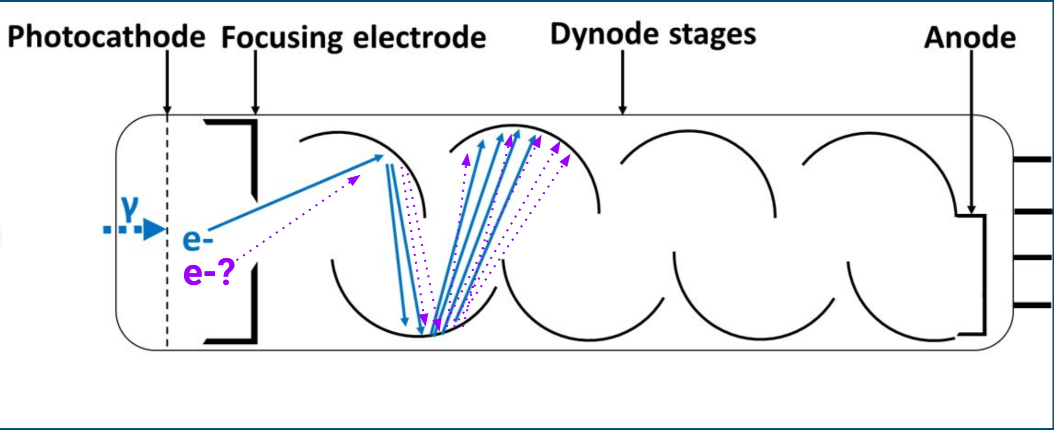
- Ideal case
  - Photon impact on photocathode, photoelectron produced, drift to surface of photocathode and emitted (Quantum Efficiency)
  - Photoelectron accelerated towards first dynode, collision emits more electrons, accelerated to following dynodes, etc.
  - Finally, electron cloud arrives at anode, where it is read out.
- Double photoelectron emission
  - VUV ~ 7eV photons
  - Can knock second electron
  - Signal can be twice as large
  - ~20% probability
  - **Key for linearity, energy resolution**
  - **$QE^{DC} \neq QE^{P}$**



Faham, C. H. et al - arXiv:1506.08748

VUV photon detection process

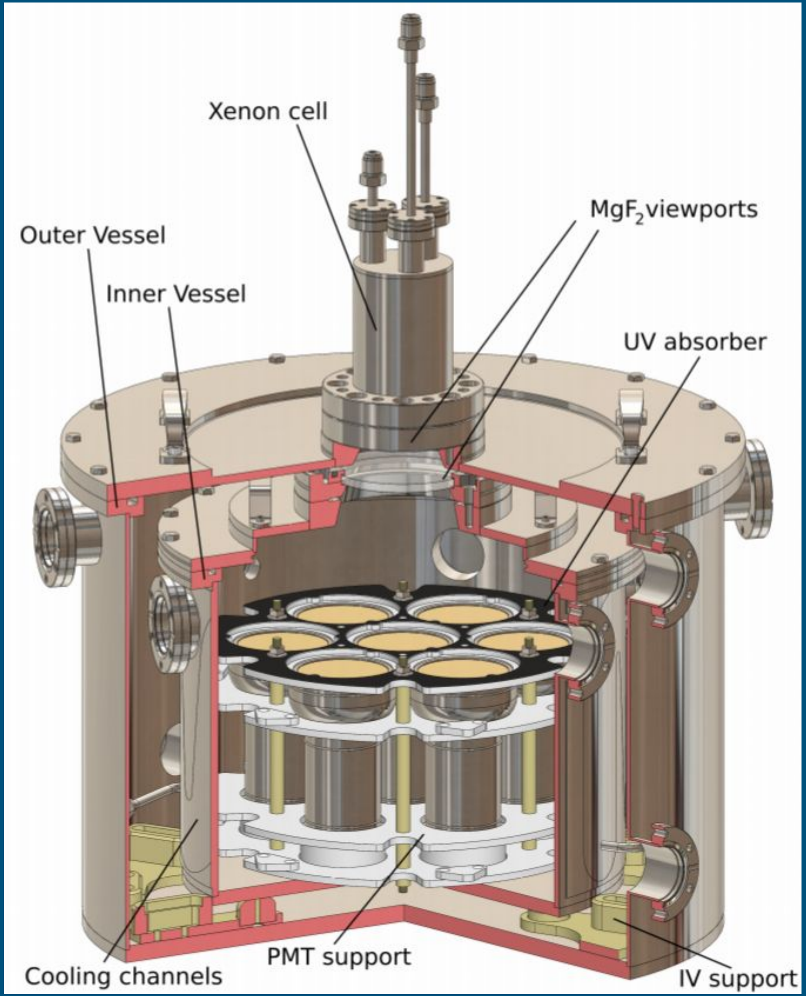
- Ideal case
  - Photon impact on photocathode, photoelectron produced, drift to surface of photocathode and emitted (Quantum Efficiency)
  - Photoelectron accelerated towards first dynode, collision emits more electrons, accelerated to following dynodes, etc.
  - Finally, electron cloud arrives at anode, where it is read out.
- Double photoelectron emission
  - VUV ~ 7eV photons
  - Can knock second electron
  - Signal can be twice as large
  - ~20% probability
  - **Key for linearity, energy resolution**
  - **$QE^{DC} \neq QE^{P}$**



Faham, C. H. et al - arXiv:1506.08748

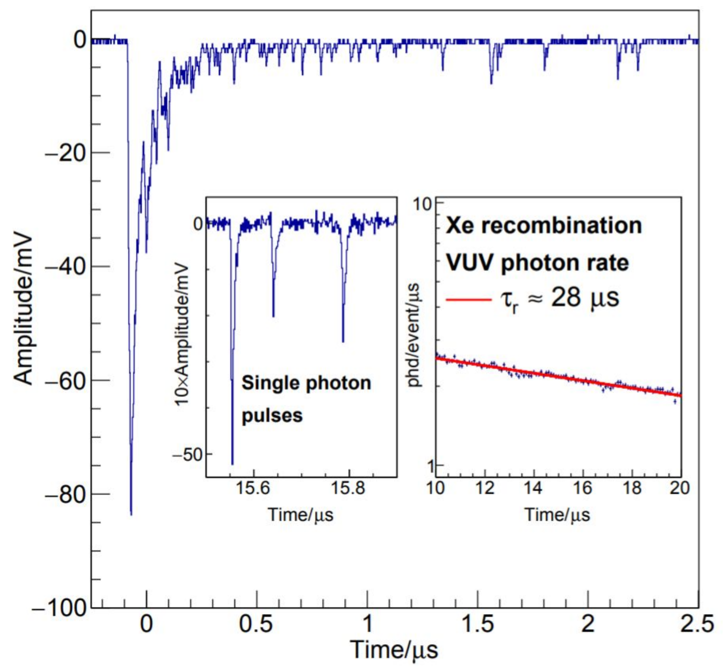
PMT characterisation at Imperial

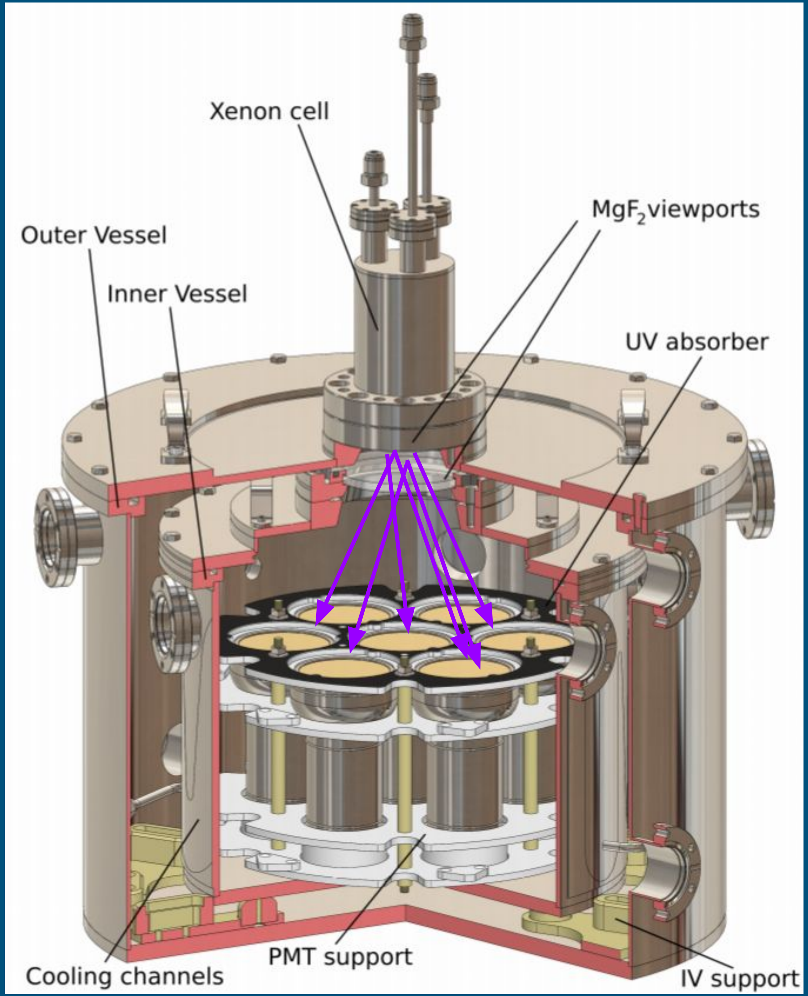
- LN2-cooled cryostat for 7 PMTs
- PMTs in 2.5 bar(a) N_2
- Illuminated by GXe scintillation cell through MgF_2 viewports
- Fibre-coupled blue LED
- Temperature control (-97.5 ±0.1)℃



B. López Paredes et al. - arXiv:1801.01597

PMT characterisation at Imperial



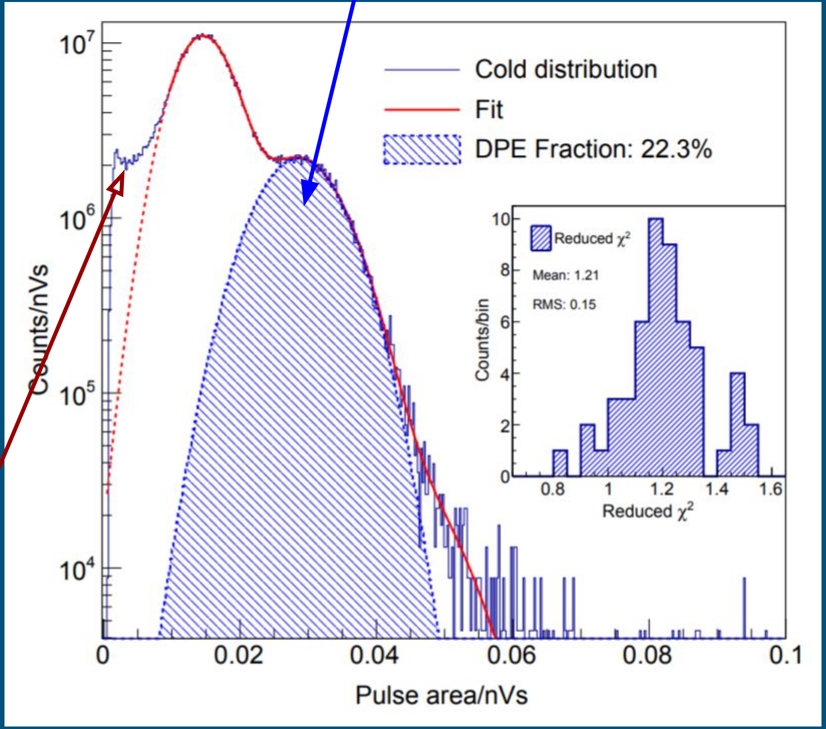


B. López Paredes et al. - arXiv:1801.01597

Characterisation of R11410-22

- Operate PMTs at gain = $5 \cdot 10^6$
- Focus first on extracting DPE fraction in VUV, main difference wrt blue response
- Fit SPE and DPE with double gaussian (μ, σ ; 2μ, $\sqrt{2}\sigma$)
- Average ~22% DPE fraction over 35 PMTs at low temperature
- Not modelling undersized pulses, develop better model to include them

1 photon = 2 photoelectrons

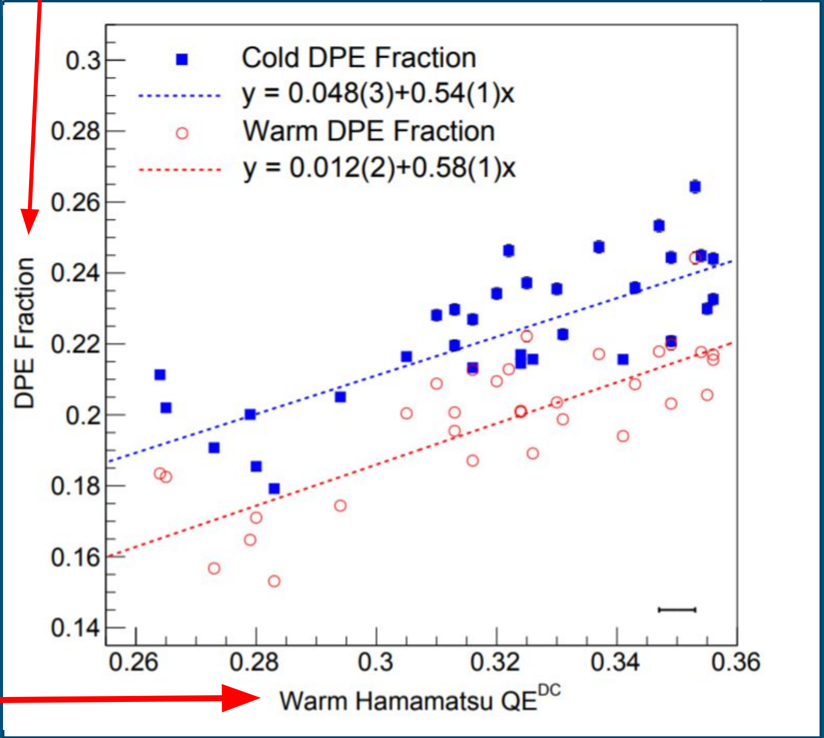


B. López Paredes et al. - arXiv:1801.01597

Characterisation of R11410-22

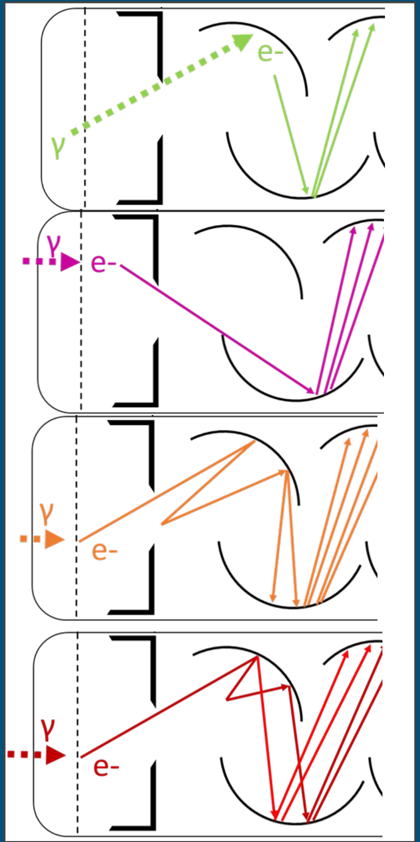
- Operate PMTs at gain = $5 \cdot 10^6$
- Focus first on extracting DPE fraction in VUV, main difference wrt blue response
- Fit SPE and DPE with double gaussian (μ, σ ; 2μ, √2σ)
- Average ~22% DPE fraction over 35 PMTs at low temperature
- Estimate double photoelectron emission fraction from QE measured at factory

Probability of 1 photon = 2 photoelectrons



B. López Paredes et al. - arXiv:1801.01597

More realistic model of single photon response

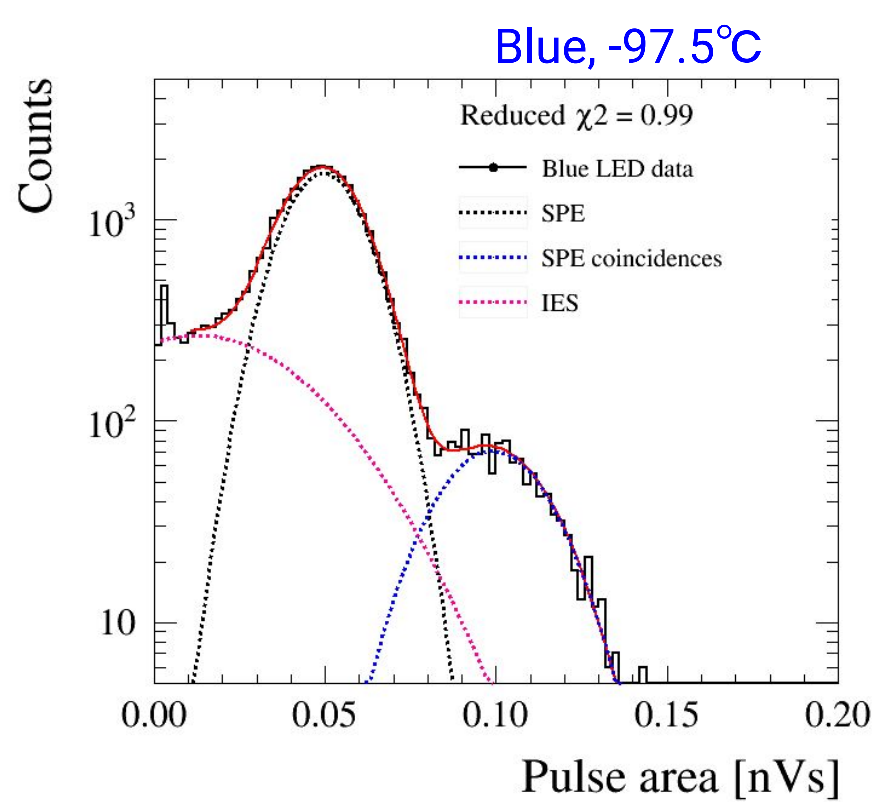


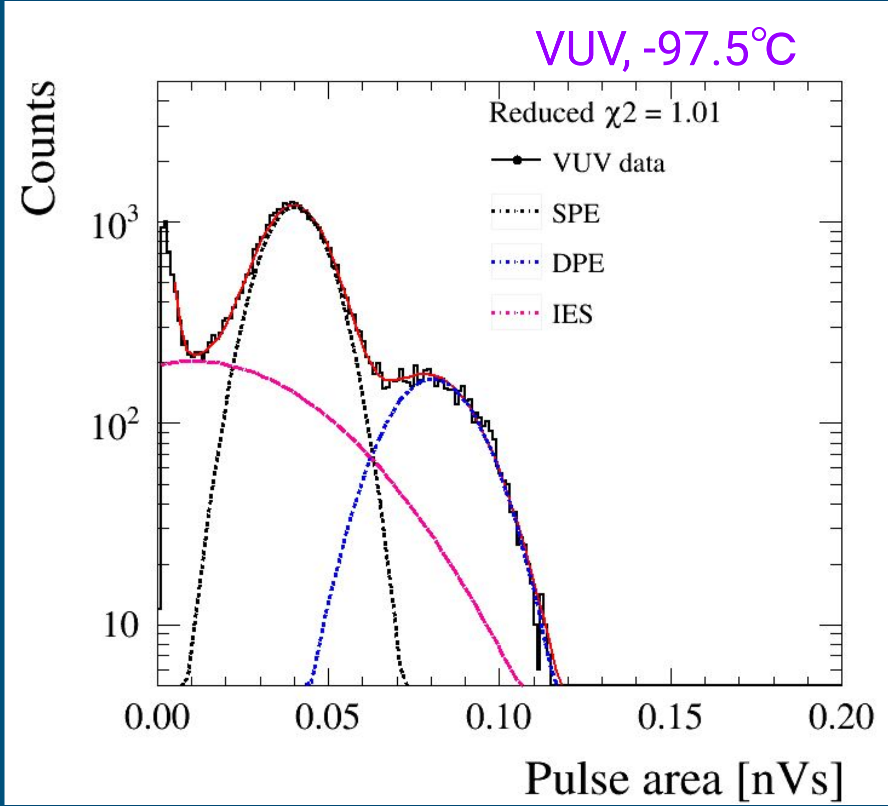
- First dynode hits:
  - Early pulses
  - Reduced gain
- Second dynode collection:
  - Early pulses
  - Slightly reduced gain
- Elastic scattering:
  - Delayed pulses
  - Nominal gain
- Inelastic scattering
  - Delayed pulses
  - Charge loss

Characterisation of R11410-22 - high gain

- Aim to observe undersized signals and understand the distribution
  - Contribution to photon detection efficiency in a real detector
- First dynode hits: ~1/14 size of SPE
- Measurement at ~ $1\text{-}3 \cdot 10^7$ gain at ambient and low temperature
  - Temperature dependence → long stabilisation period
- Blue and VUV measurements

Characterisation of R11410-22 - high gain

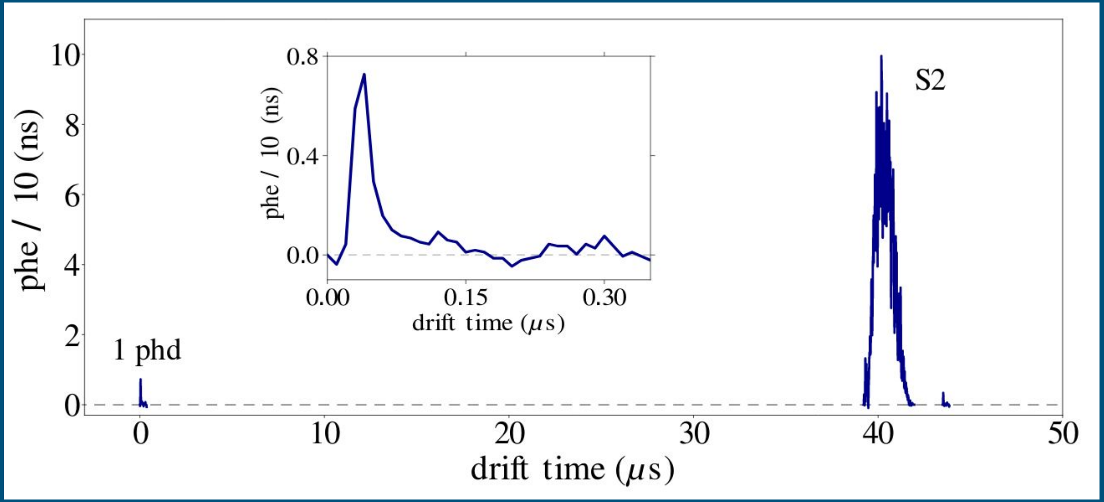


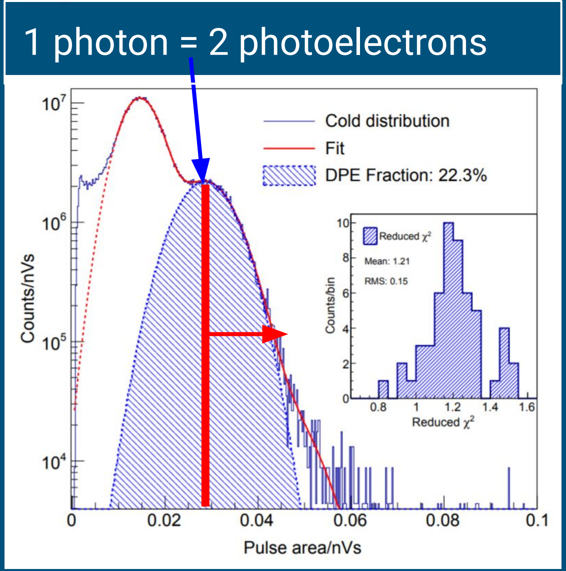


Brais López Paredes, Imperial College London

Exploiting DPE effect

- Double photoelectron emission:
  - Improve signal efficiency
  - Only VUV produces DPE with significant probability
  - Low chance of large area dark count
  - Optimise minimum DPE area (signal) to lower coincidence threshold
- LUX analysis:
  - 2phd→1phd
- LZ simulation:
  - 3phd→2phd

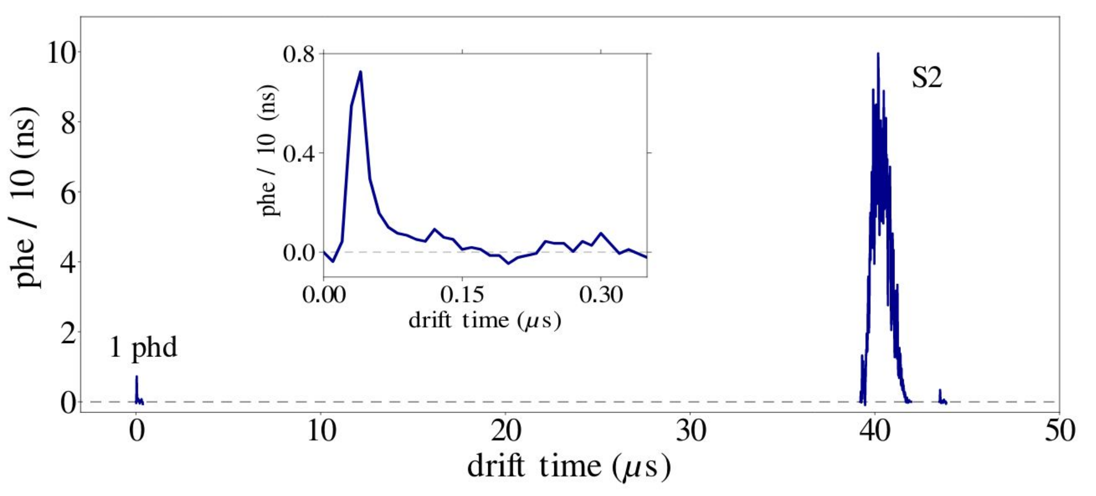




N. Marangou et al. - arXiv:1907.06272

Exploiting DPE effect

- Double photoelectron emission:
  - Improve signal efficiency
  - Only VUV produces DPE with significant probability
  - Low chance of large area dark count
  - Optimise minimum DPE area (signal) to lower coincidence threshold
- LUX analysis:
  - 2phd→1phd
- LZ simulation:
  - 3phd→2phd

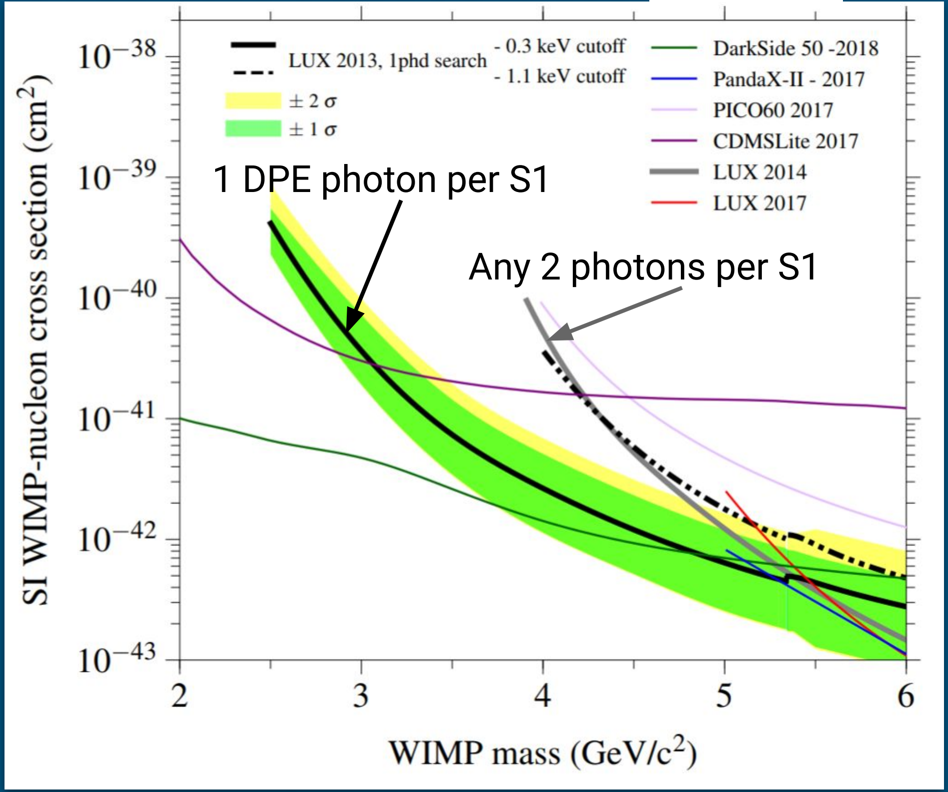


- Undersized pulses:
  - Properly model single photon response
  - Better understand efficiency
  - (Signal in noise pedestal and valley)

N. Marangou et al. - arXiv:1907.06272

Lowering the scintillation threshold in LUX

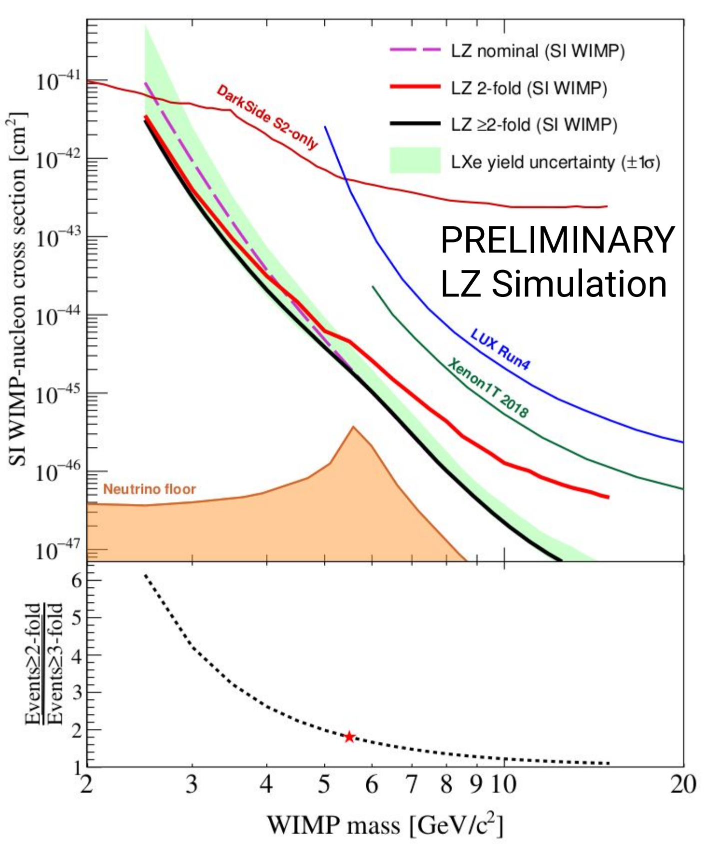
- LUX improved mass reach from 4 GeV to 2.5 GeV
- Cross section limit better by an order of magnitude at 4GeV
- Optimise cut on single-photon S1 pulse areas associated to S2s
  - Efficiency improvement at low energies↔masses
  - Demonstrated first on tritium ER calibration



N. Marangou et al. - arXiv:1907.06272

Lowering the LZ threshold

- Preliminary simulation study
- Following a similar strategy to LUX
- Nominal analysis requires a 3-fold S1 (3 phd in different PMTs within 150 ns)
  - Avoids fake S1 from random DC coincidence
- Lower to 2-fold, but require at least 1phd to be DPE, use Xe scintillation timing
  - Optimise pulse size and timing to maximise significance
- Modest improvement at low WIMP mass, but doubles ^{8}B CEνNS rate



Brais López Paredes, Imperial College London

Conclusions

- Photomultiplier response to single VUV photons not straightforward
- Good understanding and modelling needed for rare event searches
- Not only an improvement in calibration
- Response to signal (VUV) light different from dark count pulses
- Can use DPE effect to recover population of low energy events
  - Lower LXe-TPC detector threshold to search for very low energy interactions

Backup

Quantum Efficiency

Given a light pulse inducing a signal with pulse area A at the PMT anode, the absolute number of photons, N, incident on the photocathode can then be estimated as

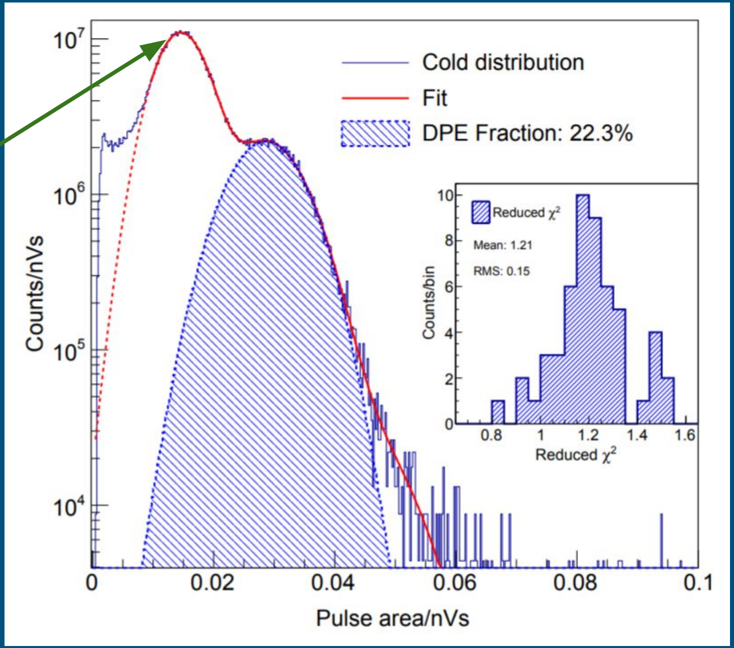
$$N = \frac{A}{\eta\, \mu\, QE^{\mathrm{P}}} = \frac{A}{\eta\, \mu_1\, QE_{\mathrm{H}}^{\mathrm{DC}}}\,, \qquad (5)$$

Photon counting vs DC current measurement

$$QE^{\mathrm{P}} = \frac{\mu_1}{\mu} QE_{\mathrm{H}}^{\mathrm{DC}}$$

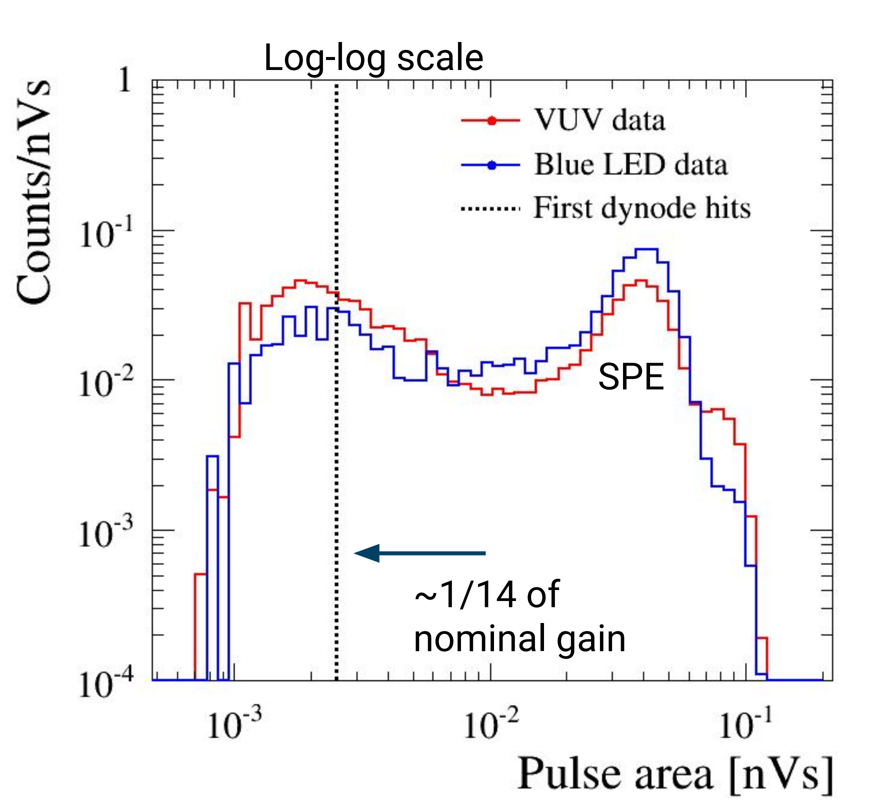
μ_1

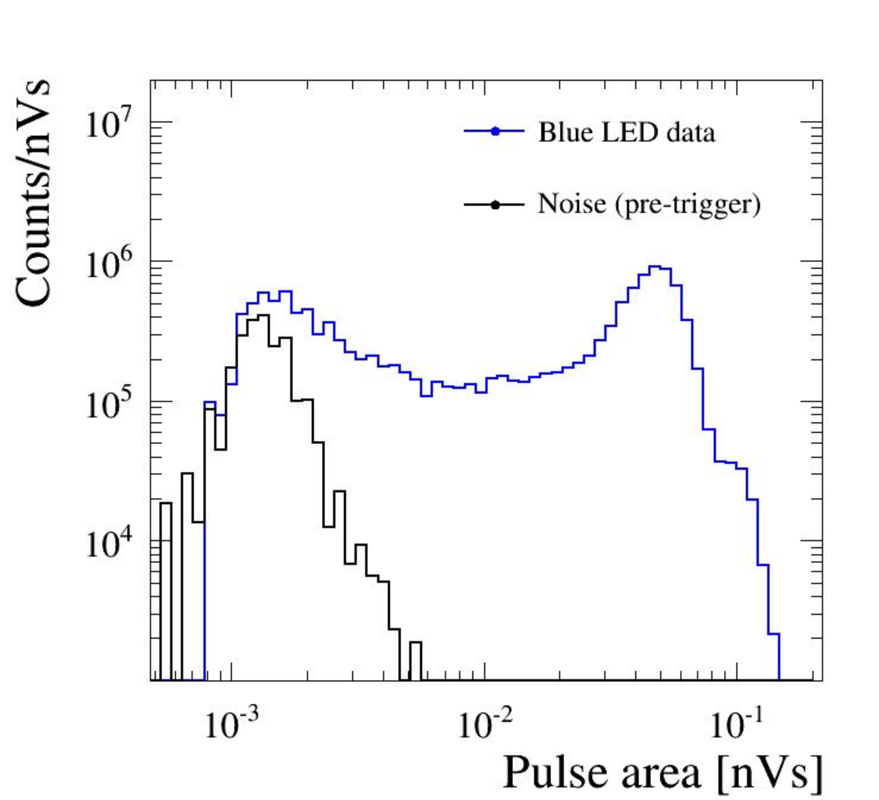
$\mu = (1+\mathrm{DPE})\cdot\mu_1$



QE^{P} must be used when doing photon counting in the VUV

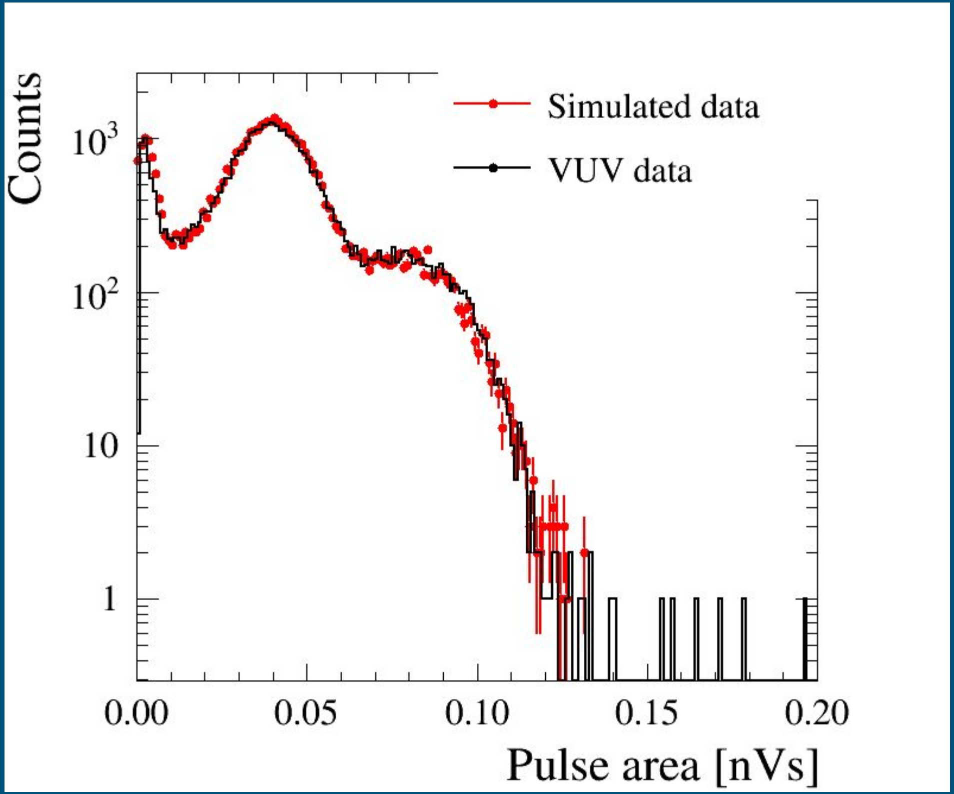
Characterisation of R11410-22 - high gain





Reconstructing PMT parameters

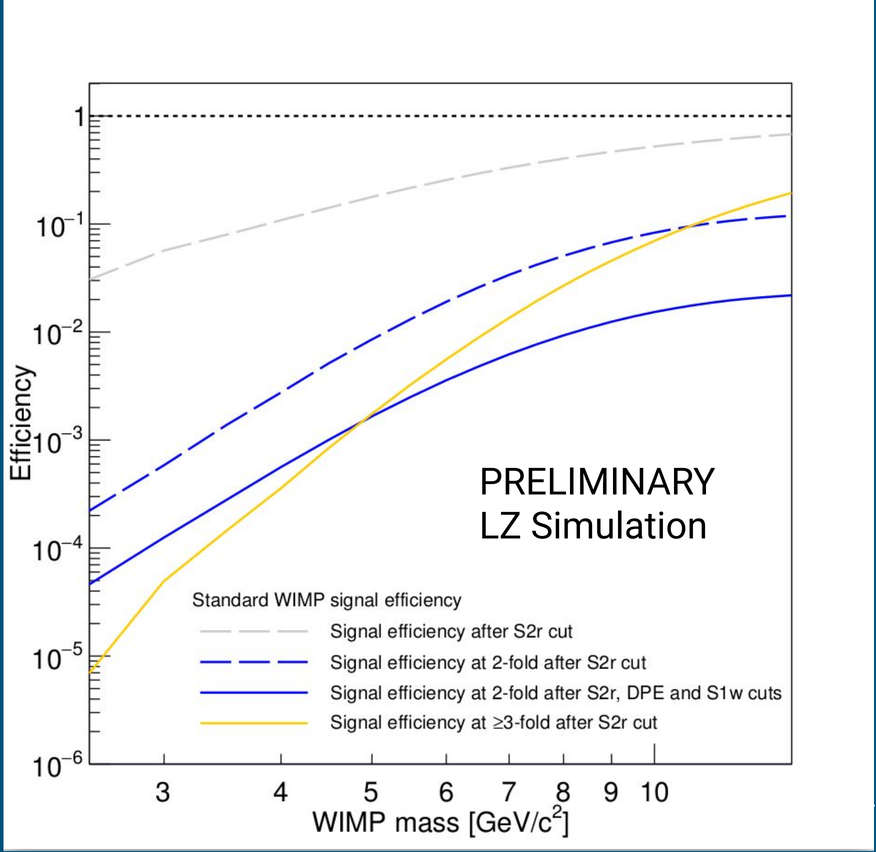
- Given DPE, hard to disentangle secondary effects
  - DPE+inelastic scattering, second dynode collection, etc
- Electronics simulation, variation of parameters
- First Dynode Hits: 8%
- Double Photoelectron Emission: 18%
- (~20% wrt SPE+DPE)



Brais López Paredes, Imperial College London

LZ signal efficiency at 2 and 3 fold

- 2 fold analysis overtakes nominal at low masses



Modelling inelastic scattering

Model as poisson with a fraction of the SPE mean (f = charge loss).

Can approximate quite well with a gaussian as shown.

First dynode is the main contribution to the width.

Modelling dy1 inelastic scattering

$\text{Poisson}((1-f^{\,Q\,loss})\cdot\mu^{SPE})\sim\text{Gaus}$